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SECURITY CLASSIFICATION OF THIS PAGE

AD-A204 440

REPORT DOCUMENTATION PAGE

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ARO 23418.1-GS

6a. NAME OF PERFORMING ORGANIZATION
Oak Ridge National Lab.

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
U. S. Army Research Office

6c. ADDRESS (City, State, and ZIP Code)
Oak Ridge, TN 37830

7b. ADDRESS (City, State, and ZIP Code)
P. O. Box 12211
Research Triangle Park, NC 27709-2211

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
U. S. Army Research Office

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
MIPR ARO 128-87

8c. ADDRESS (City, State, and ZIP Code)
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
An Investigation of the Intermittent Turbulent Breakdown of the Nocturnal Planetary Boundary Layer

12. PERSONAL AUTHOR(S)
Carmen J. Nappo

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM 4/1/87 TO 3/31/88

14. DATE OF REPORT (Year, Month, Day)
15 Oct 88

15. PAGE COUNT
13

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Turbulent Breakdown, Boundary Layers, Turbulence, Wind Speeds, Complex Terrain, Flat Terrain

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A study of the statistics of the intermittent turbulent breakdown of the stable boundary layer over flat and complex terrain was made. The study is based on the temporal behavior of the covariance of wind speed and temperature, C_{ST}. During a breakdown event, the overturning of the PBL results in high-speed warm air being transported downward

AD-A201 743

DTIC ELECTE 24 FEB 1989 S

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

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UNCLASSIFIED

toward the ground surface, and low-speed cool air being transported upward away from the ground surface. This results in a positive value of C_{ϑ_T} and a consequent flux of heat toward the ground surface.

The following general conclusions are reached:

1. Over uniform terrain, the characteristics of breakdown events differ between urban and rural environments.

2. Over complex terrain, the characteristics of breakdown events differ between high and low wind speed nights.

3. On average, the number of breakdowns per night is about 10 with an average duration of about 20 minutes.

4. In rural environments or for low wind speed nights in complex terrain, breakdown events make significant contributions to the nightly flux of heat to the ground surface.

ARO 23418.1-GS

AN INVESTIGATION OF THE INTERMITTENT TURBULENT BREAKDOWN OF THE NOCTURNAL PLANETARY BOUNDARY LAYER

Carmen J. Nappo

FINAL REPORT

15 October, 1988

U. S. ARMY RESEARCH OFFICE

DOE INTERAGENCY AGREEMENT NO. 40-833-84

ARMY NO. ARO 128-87

Air Resources Laboratory
Atmospheric Turbulence and Diffusion Division
National Oceanic and Atmospheric Administration
P. O. Box 2456, Oak Ridge, TN 37831

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1. INTRODUCTION

This report presents the essential results of a study of the statistics describing the intermittent breakdowns of the stable planetary boundary layer (PBL). The objectives of this research are to:

1. Formulate a qualitative model of the physical mechanisms leading to breakdowns.
2. Evaluate the frequency, intensity, and duration of breakdown events.
3. Determine the time and space scales of these events.

This research originally centered on an analysis of the EPA Regional Atmospheric Monitoring System (RAMS) data collected within and around St. Louis, MO from 1975 to 1977. However, it was recognized early in the program that similar data could be obtained at the Walker Branch field site near Oak Ridge, TN, and that these data would introduce into the research the contrasting situation of complex terrain.

2. THE DATA

The locations of the RAMS stations are shown in Figure 1. The monitoring stations were arranged in approximate rings with average radii from the central urban station (101) of 5, 11, 20 and 44 kilometers. The data collected at each station are in the form of one-minute averages. In the research described here, we use only the wind speed, temperature, and ozone mixing ratio data. The monitoring system at the Walker Branch site consistes of a three-component Gill anemometer, an aspirated bead thermistor, and a Meloy continuous-measuring ozone monitor all mounted at the 40 m level of the Walker Branch tower. This level is some 17 m above the forest canopy. The tower rests on the crest of a ridge which has an average elevation of about 60 m above the floor of the Tennessee River Valley. This is a region of complex terrain consisting of parallel ridges and valleys aligned along the valley axis. Observations are taken every half-second, and from these one-minute averages are formed. In addition to these measurements, a monostatic sodar was in operation in a clearing about 400 m away.

The data are first screened for continuity, and only those nights with more than 80 percent data recovery are examined. Missing data are accounted for by assigning to these points the most recent valid value. For the Walker Branch site, 87 nights of data were used. The analyses of the RAMS data centered on Stations 1 and 23 which contrasts urban with rural environments. For Station 1, 78 nights of data were used, and for Station 23, 53 nights were used.

3. METHOD OF ANALYSIS

The crux of the analysis lies in the isolation of breakdown events from the time series of wind speed, temperature and ozone mixing ratio. This is done with the following qualitative model of the breakdown process. In the stable PBL near the ground surface, wind speed, temperature and ozone mixing ratio tend to increase linearly with height above the ground surface. The breakdown event is pictured as an overturning of the PBL air which results in high-speed, warm and ozone-rich air being brought down toward the ground surface while low-speed, cool and ozone-poor air is being brought upward away from the ground surface. This overturning results in fluxes of heat, F_H, and ozone, F_O, directed toward the ground surface. These fluxes are given by

$$F_H = -Dc_pC_{ST}$$

$$F_O = -DC_{SO}$$

where D is the density of air, c_p is the specific heat for air at constant pressure, C_{ST} is the covariance of wind speed and temperature, and C_{SO} is the covariance of wind speed and ozone. The covariances are calculated at each data point in the time series using

$$C_{ST} = (s-S)(t-T)$$

$$C_{SO} = (s-S)(o-O)$$

where s, t, and o are the one-minute, smoothed, values of wind speed, temperature, and ozone respectively, and S, T, and O are 120-minute running means of these variables. Examples of C_{ST} and C_{SO} observed at the Walker Branch site are shown in Figure 2. In each case, the covariances are predominantly positive throughout the night. The same types of patterns are also observed in the RAMS data. We see from these figures that the covariances of wind speed-temperature and wind speed-ozone are essentially identical. This is because the overturning of the PBL during a breakdown event affects equally the temperature and ozone fields. Thus, we need only look at C_{ST} to formulate statistics of the breakdowns.

The relationship between breakdowns and turbulence in the PBL is illustrated in Figure 3 where the graph of C_{ST} versus time is superimposed on the sodar trace for a typical night at the Walker Branch site, 16-17 October, 1987. The covariance is essentially zero until just before 2200 hours when a sharp rise occurs. This rise in C_{ST} corresponds with the sudden appearance of turbulence in the PBL as indicated by the sodar trace. After this initial period, the covariance and the turbulence are seen to vary with time in a complex way. At about 0400 hours, PBL turbulence and C_{ST} drop to zero and so remain. Large negative covariances such as those seen at 0215 and 0330 hours in Figure 3 are often seen in the Walker Branch and the RAMS data. These episodes remain to be explained.

We wish to determine the frequencies of occurrences and durations of breakdown events. A breakdown event and its duration is determined by the time during which C_{ST} is greater than a threshold value of 0.05. If a threshold value is not used, then the covariances are dominated by one-minute fluctuations. These fluctuations represent a "noise" component introduced into the covariances by the finite sensitivity of the instruments. For example, the starting speed for the RAMS anemometer is 0.22 ms^{-1}, and the temperature probe has a resolution of about 0.2 °C.

4. RESULTS

Figure 4 shows histograms of the normalized frequencies of occurrences of bursts per night for urban (Station 1) and rural (Station 23) environments. We see that on average both stations experience approximately 8 bursts per night; however, the urban station shows a greater range of breakdown frequencies than the rural station. The normalized frequencies of occurrences of the durations of the bursts at these stations are presented in Figure 5. The histogram for Station 1 shows several well defined peaks, but clearly, the majority of the bursts have durations less than 10 minutes. For Station 23, the distribution of burst durations is rather uniform for times less than about 20 minutes; the number of bursts with durations longer than 20 minutes is greater at this station than at Station 1.

To examine the effects of wind speed on the breakdown statistics at the Walker Branch site, the data were separated into low ($< 2\ ms^{-1}$) and high ($> 2\ ms^{-1}$) night-time-averaged wind speed classes. Figure 6 shows the histograms of the normalized frequencies of occurrences of bursts per night for these two wind classes. Although the average number of bursts per night are about the same, the low-speed frequency distribution is skewed toward low values, and the high-speed frequency distribution is skewed toward high values. The durations of these bursts are shown in Figure 7. For the low-speed nights, the durations of the breakdowns are significantly longer than for the high-speed nights.

In Figures 5 and 7, all burst durations greater than 60 minutes are placed in the 60-minute bin. From the RAMS data, Figure 5, we see that there are more breakdowns with durations greater than 60 minutes for the rural station than for the urban station. For the low-speed case at the Walker Branch site, Figure 7, there are more breakdowns with durations greater than 60-minutes than for the high-speed case. However, it is felt that periods of positive covariance longer than 30 minutes are not necessarily due to turbulence, but rather mesoscale processes such as the passages of fronts or intense thunderstorms. The effects of a large, rapid change in either wind speed or temperature will persist in the filtered data for a considerable time even with a 120-minute running mean.

Table 1 presents some average values associated with bursting events. We see that on average, the number of breakdowns per night are greater over complex terrain than over uniform terrain. Over the uniform terrain, the average heat flux per burst is slightly greater over the rural site than over the urban site. Over complex terrain, the average heat flux per burst is twice as great for low wind speed nights than for high wind speed nights. The average night-time heat flux is obtained by averaging the covariances over the entire night, and then averaging these values over all the nights. For the urban station, the average night-time heat flux is about 62 percent less than the average heat flux associated with bursts; for this case, we speculate that breakdown events contribute relatively little to the night-time heat flux. However, for the rural station the average night-time heat flux is about 48 percent greater than that associated with breakdowns, and we speculate that for this case breakdowns contribute significantly to the night-time heat flux. At the Walker Branch site for low wind speed nights, the average night-time heat flux is about 45 percent greater than that associated with breakdowns, and we speculate that breakdown events contribute significantly to the average night-time heat flux. However, for high wind speed nights the sign of the average night-time heat flux is opposite to that for the breakdown events, and we speculate that in this case the breakdowns contribute very little to the night-time heat flux. The average duration of breakdowns is greater over the rural environment (Station 23) than over the urban environment (Station 1). Over the complex terrain site, the duration of breakdowns during low wind speed nights is greater than during high wind speed nights.

5. CONCLUSIONS

A study of the statistics of the intermittent turbulent breakdown of the stable boundary layer over flat and complex terrain was made. The study is based on the temporal behavior of the covariance of wind speed and temperature, C_{ST}. During a breakdown event, the overturning of the PBL results in high-speed warm air being transported downward toward the ground surface, and low-speed cool air being transported upward away from the ground surface. This results in a positive value of C_{ST} and a consequent flux of heat toward the ground surface.

The following general conclusions are reached:

1. Over uniform terrain, the characteristics of breakdown events differ between urban and rural environments.

2. Over complex terrain, the characteristics of breakdown events differ between high and low wind speed nights.

3. On average, the number of breakdowns per night is about 10 with an average duration of about 20 minutes.

4. In rural environments or for low wind speed nights in complex terrain, breakdown events make significant contributions to the night-time flux of heat to the ground surface.

CAPTIONS

Figure 1. The RAMS stations in and around St. Louis, MO.

Figure 2. Covariances of wind speed-temperature and wind speed-ozone at the Walker Branch field site.

Figure 3. Wind speed-temperature covariance and monostatic sodar trace for 16-17 October, 1987 at the Walker Branch field site.

Figure 4. Histograms of normalized frequencies of occurrences of bursting events for urban (Station 1) and rural (Station 23) RAMS stations.

Figure 5. Histograms of normalized frequencies of occurrences of burst durations for urban (Station 1) and rural (Station 23) RAMS stations.

Figure 6. Histograms of normalized frequencies of occurrences of bursting events for low and high wind speed nights at the Walker Branch field site.

Figure 7. Histograms of normalized frequencies of occurrences of burst durations for low and high wind speed nights at the Walker Branch field site.

TABLE 1

AVERAGE VALUES ASSOCIATED WITH BURSTING EVENTS

	RAMS		WALKER BRANCH	
	URBAN (#1)	RURAL (#23)	< 2 M/S	> 2 M/S
BURSTS/NIGHT	7	8	11	11
HEAT FLUX/BURST (W/M^2)	-29.1	-34.1	-53.1	-22.4
NIGHTLY HEAT FLUX (W/M^2)	-11.1	-50.5	-77.0	17.1
DURATION OF BURSTS (MIN)	15	19	23	16

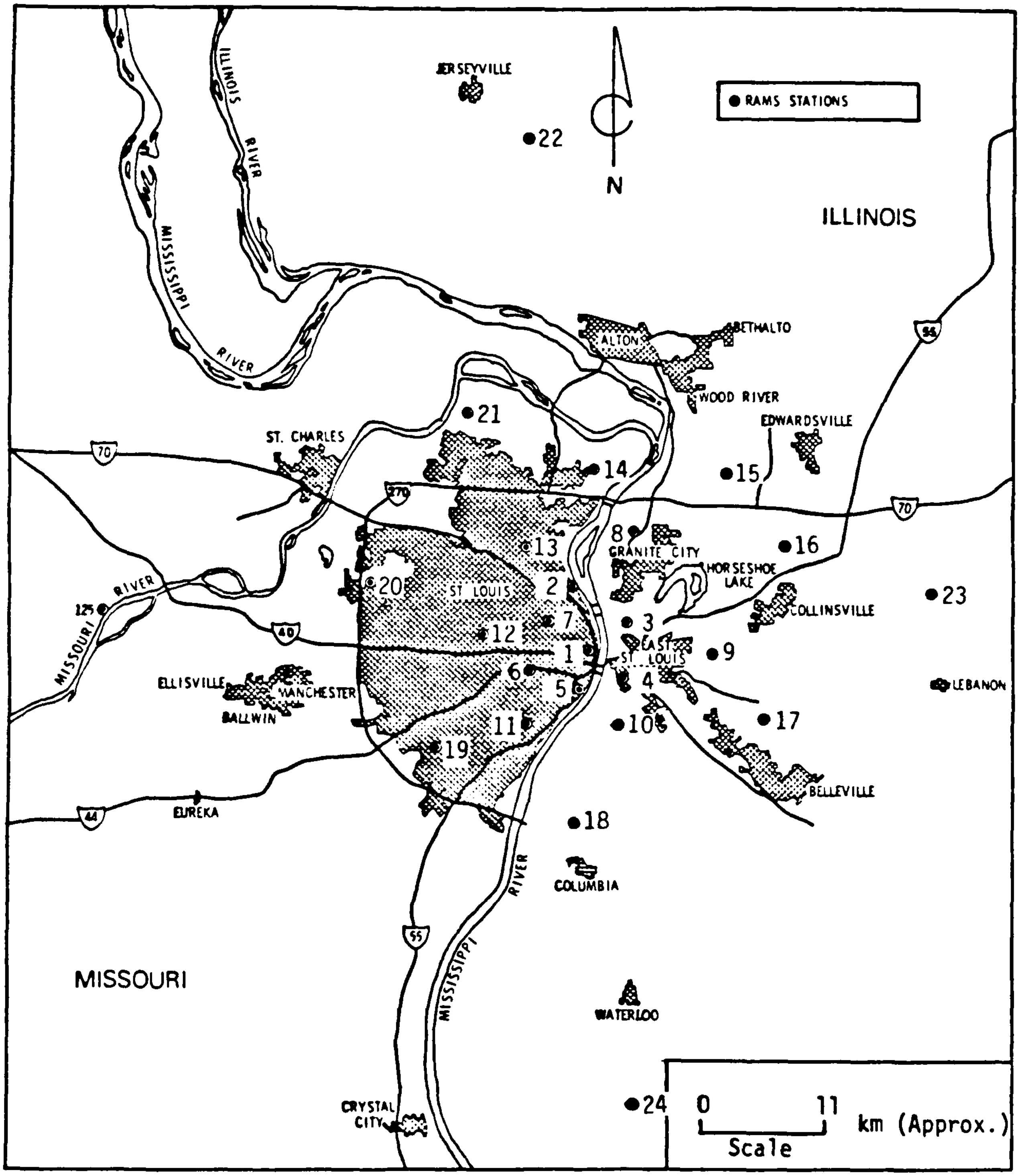

JERSEYVILLE
22
N
RAMS STATIONS
ILLINOIS
ILLINOIS RIVER
MISSISSIPPI RIVER
ALTON
BETHALTO
WOOD RIVER
EDWARDSVILLE
21
ST. CHARLES
70
14
15
270
8
GRANITE CITY
16
13
HORSESHOE LAKE
MISSOURI RIVER
125
20
ST LOUIS
2
23
COLLINSVILLE
7
3
40
12
EAST ST. LOUIS
1
9
ELLISVILLE
MANCHESTER
BALLWIN
6
5
4
LEBANON
11
10
17
19
BELLEVILLE
44
EUREKA
18
COLUMBIA
RIVER
55
MISSISSIPPI
MISSOURI
WATERLOO
CRYSTAL CITY
24
0
11
km (Approx.)
Scale

FIGURE 1

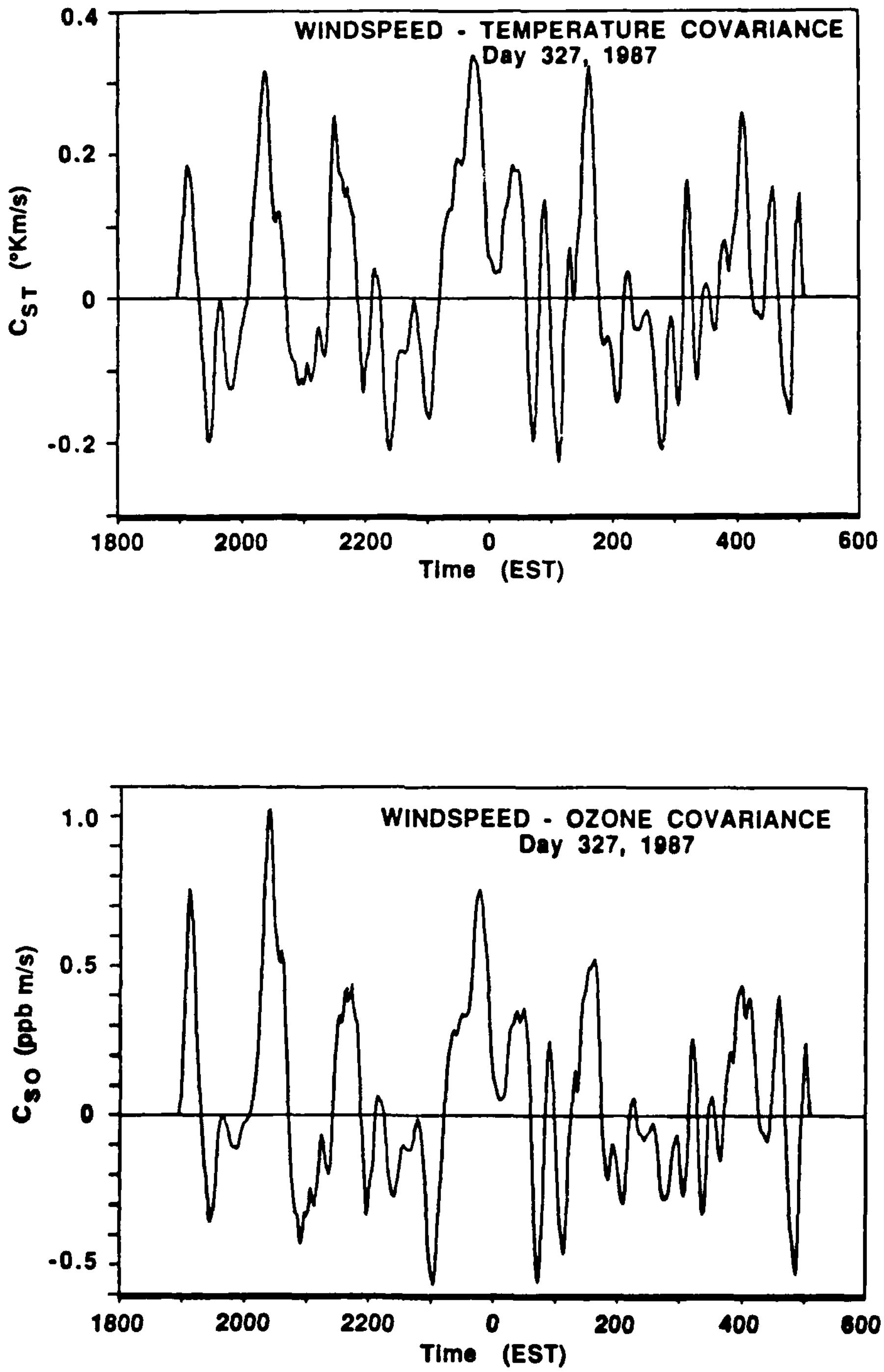

WINDSPEED - TEMPERATURE COVARIANCE
Day 327, 1987
0.4
0.2
0
-0.2
C_{ST} (°Km/s)
1800
2000
2200
0
200
400
600
Time (EST)
WINDSPEED - OZONE COVARIANCE
Day 327, 1987
1.0
0.5
0
-0.5
C_{SO} (ppb m/s)
1800
2000
2200
0
200
400
600
Time (EST)

FIGURE 2

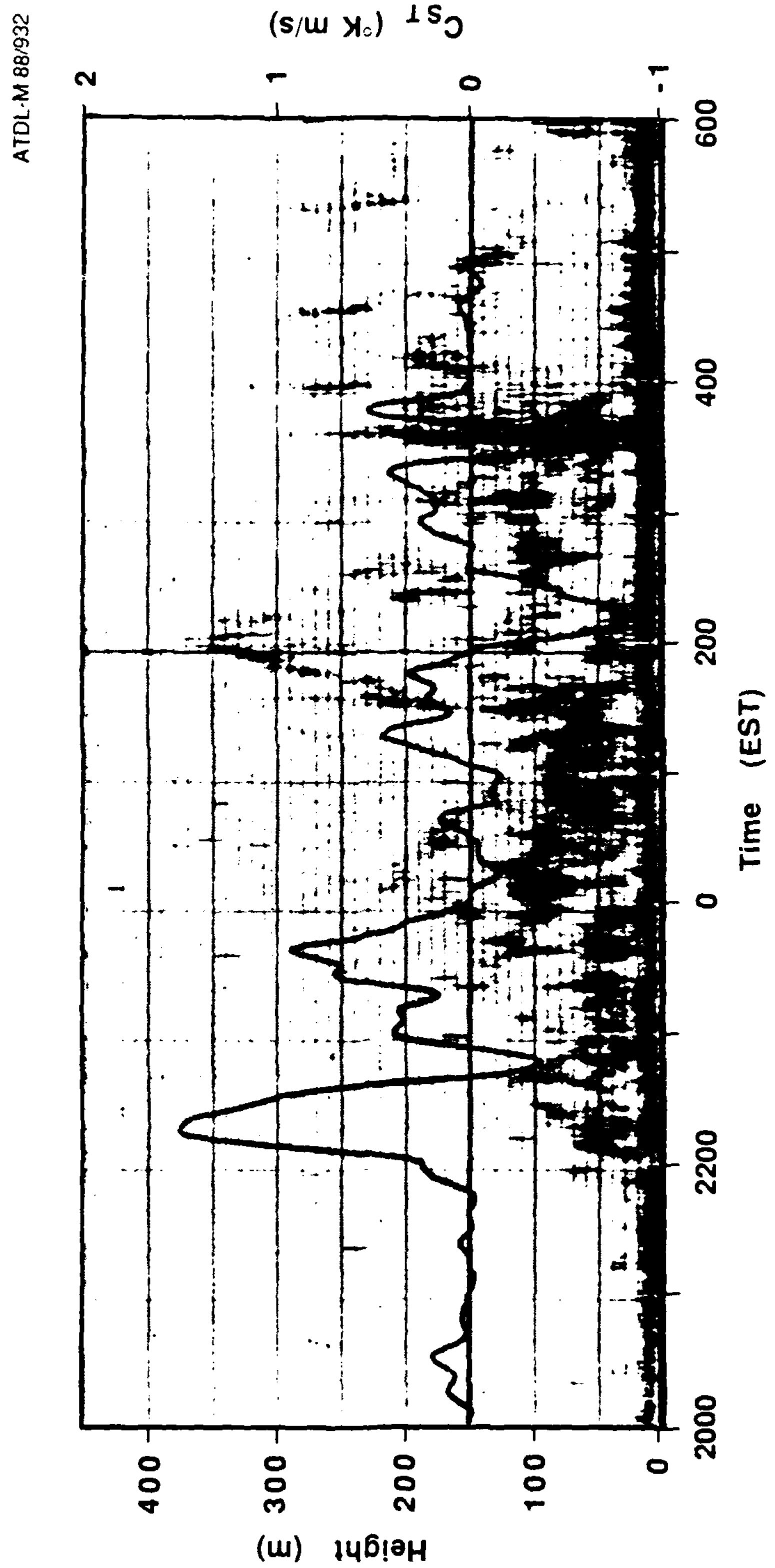

ATDL-M 88/932
Height (m)
Time (EST)
C_{ST} (°K m/s)
400
300
200
100
0
2000
2200
0
200
400
600
2
1
0
-1

FIGURE 3

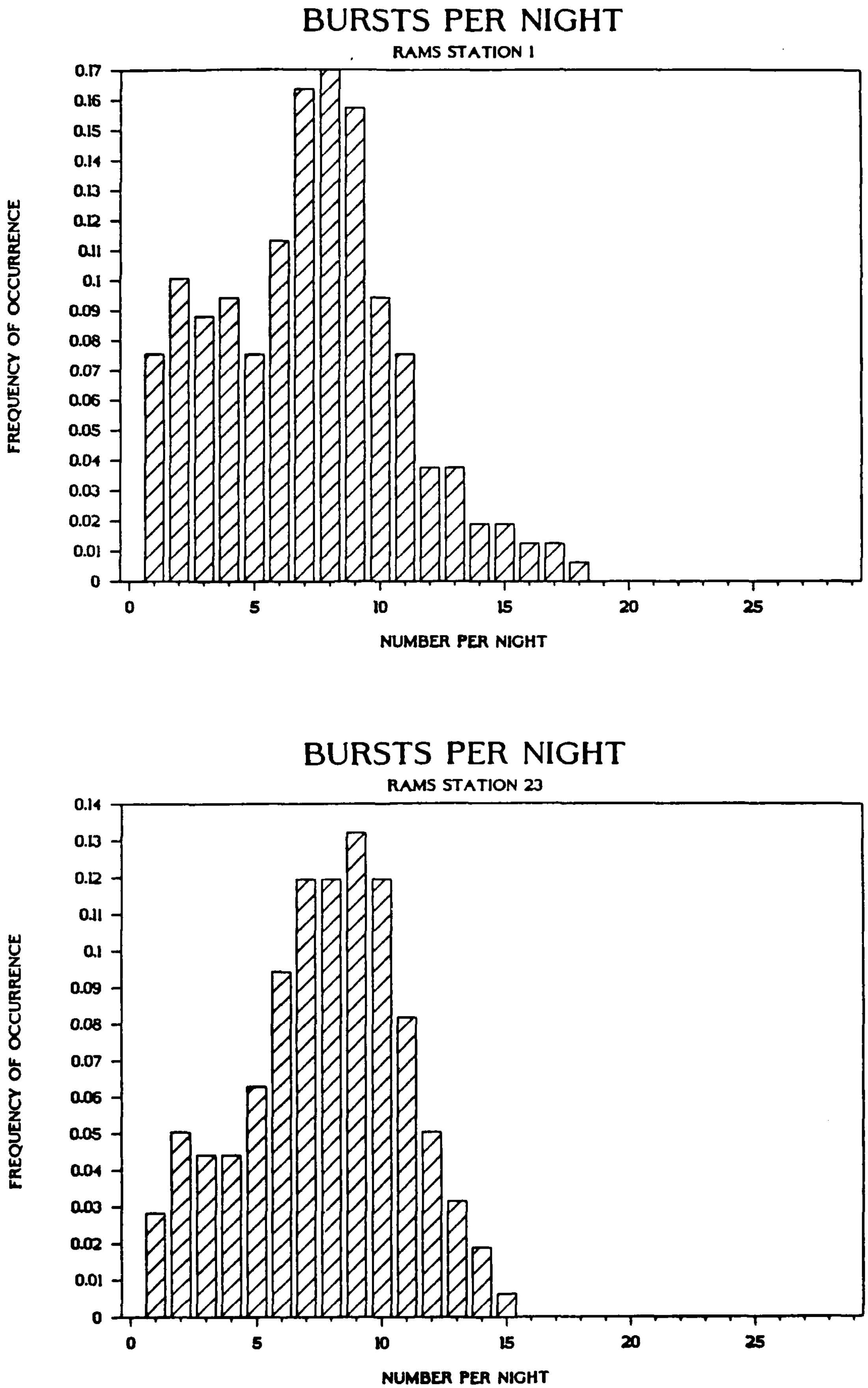
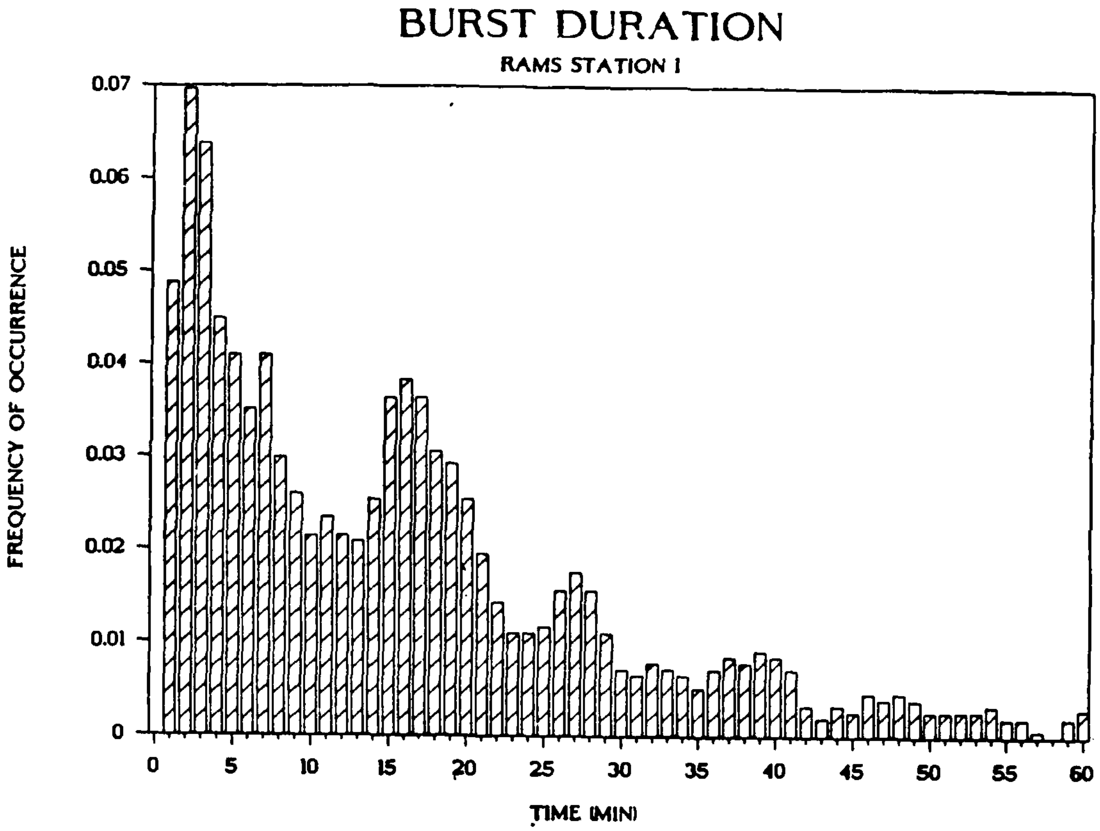

BURSTS PER NIGHT
RAMS STATION 1
FREQUENCY OF OCCURRENCE
NUMBER PER NIGHT
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0
5
10
15
20
25
BURSTS PER NIGHT
RAMS STATION 23
FREQUENCY OF OCCURRENCE
NUMBER PER NIGHT
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0
5
10
15
20
25

FIGURE 4


BURST DURATION
RAMS STATION 1
FREQUENCY OF OCCURRENCE
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 5 10 15 20 25 30 35 40 45 50 55 60
TIME (MIN)

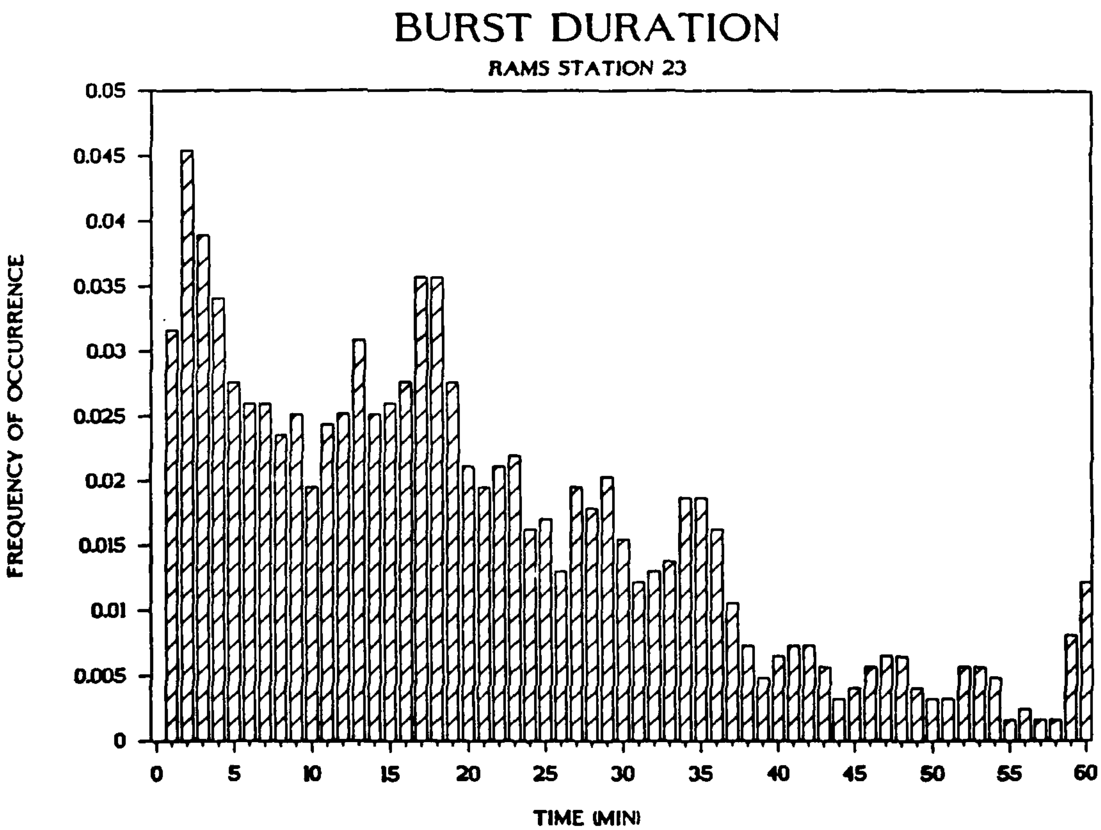
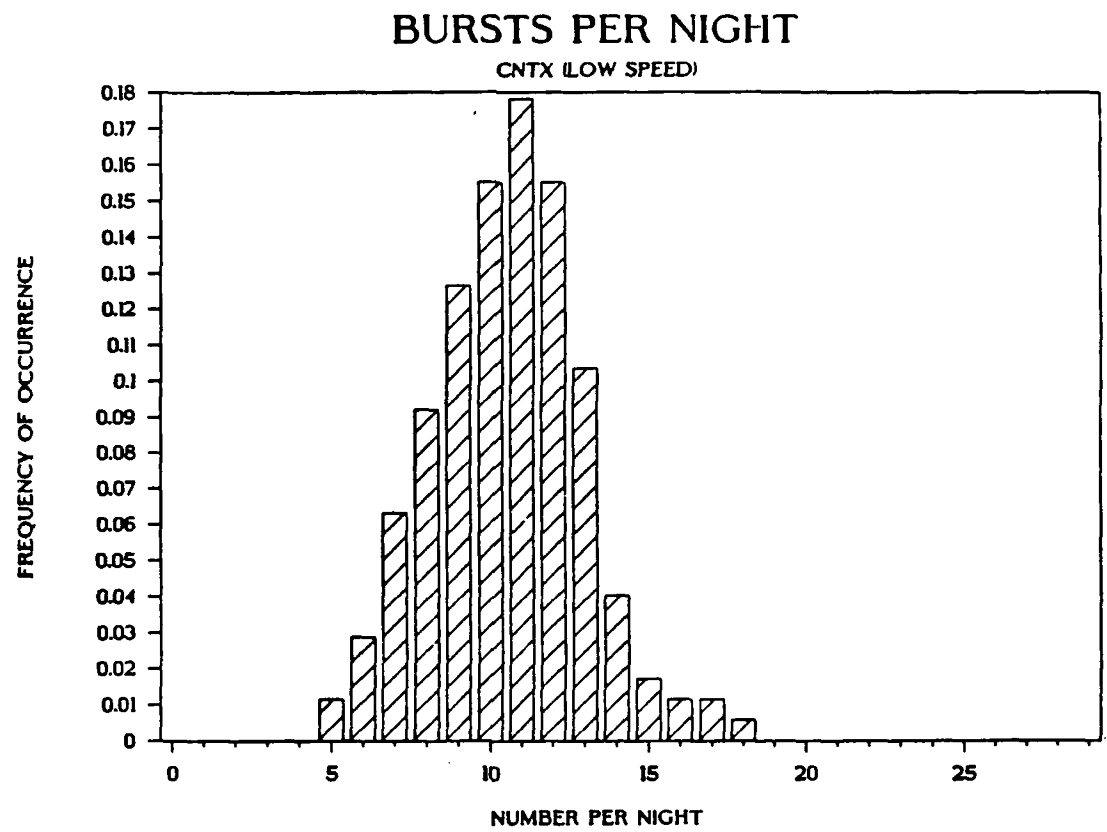

BURST DURATION
RAMS STATION 23
FREQUENCY OF OCCURRENCE
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 5 10 15 20 25 30 35 40 45 50 55 60
TIME (MIN)

FIGURE 5


BURSTS PER NIGHT
CNTX (LOW SPEED)
FREQUENCY OF OCCURRENCE
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0
5
10
15
20
25
NUMBER PER NIGHT

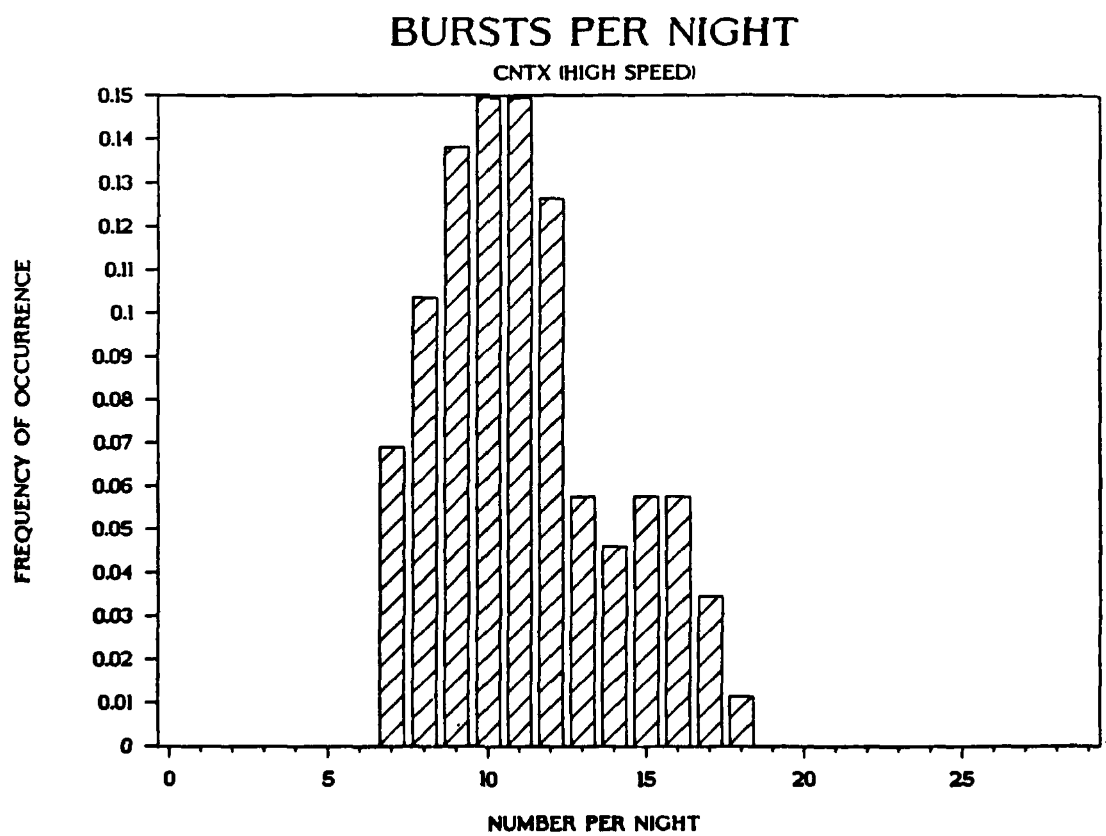
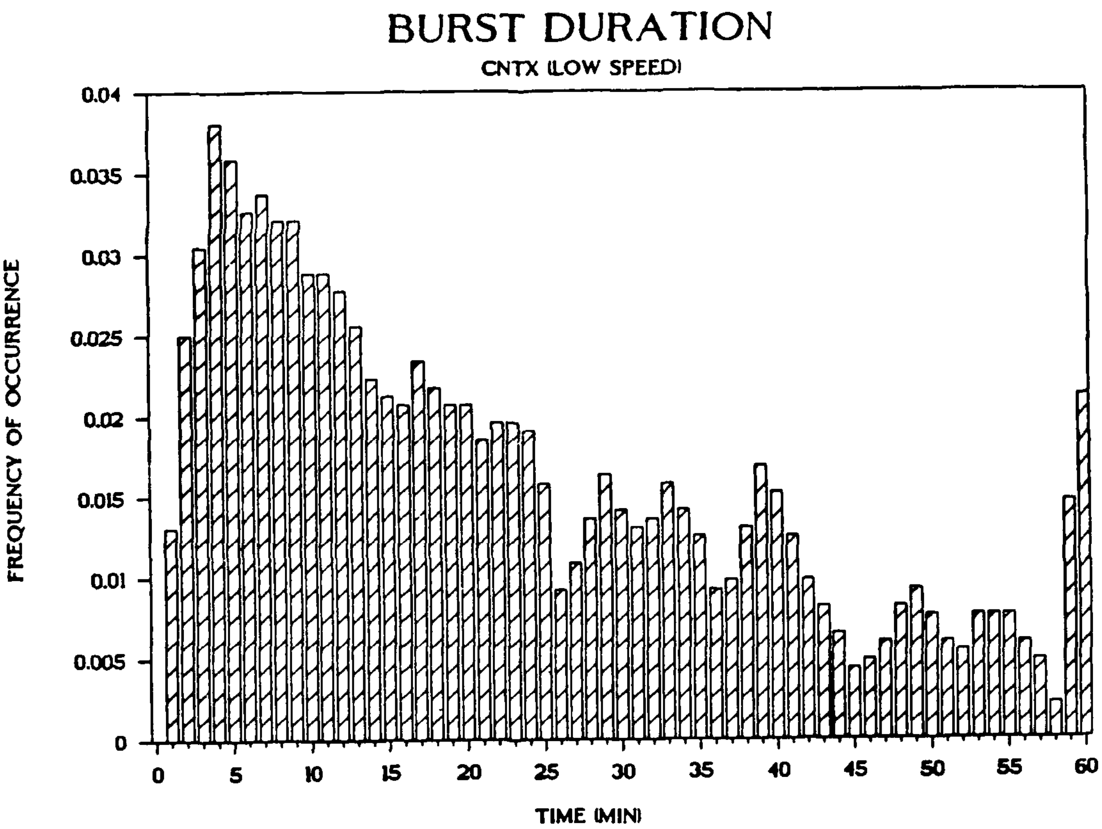

BURSTS PER NIGHT
CNTX (HIGH SPEED)
FREQUENCY OF OCCURRENCE
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0
5
10
15
20
25
NUMBER PER NIGHT

FIGURE 6


BURST DURATION
CNTX (LOW SPEED)
FREQUENCY OF OCCURRENCE
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20
25
30
35
40
45
50
55
60
TIME (MIN)

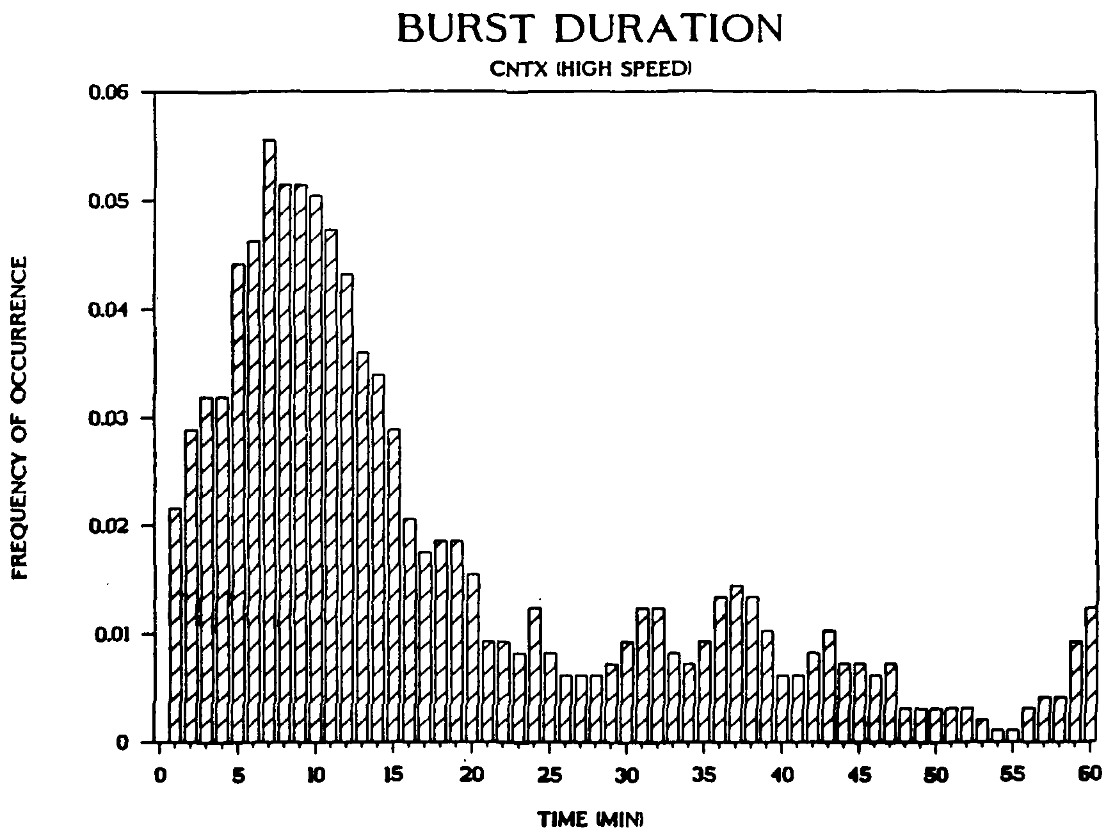

BURST DURATION
CNTX (HIGH SPEED)
FREQUENCY OF OCCURRENCE
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
30
35
40
45
50
55
60
TIME (MIN)

FIGURE 7